Channel Access Scheduling in Ad Hoc Networks with Unidirectional Links *

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ABSTRACT

A new family of collision-free channel access protocols for ad hoc networks with unidirectional links is introduced. These protocols are based on a distributed contention resolution algorithm that operates at each node based on the list of direct contenders (one-hop neighbors or incident links) and indirect interferences (two-hop neighbors and related links). Depending on the activation scheme (node activation or link activation), a network node uses the identifiers of its neighbors one and two hops away to elect deterministically one or multiple winners for channel access in each contention context (e.g., a time slot or a frequency band). The protocols are shown to be fair and capable of achieving maximum utilization of the channel bandwidth. The delay and throughput characteristics of the channel access protocols is studied by simulations.

1. INTRODUCTION

Many routing protocols ([1] [2] [10] [12] [14] [15] [23]) have been proposed in the recent past to take advantage of the existence of unidirectional links and improve network throughput in ad hoc networks. However, there has been very little progress in the corresponding channel access mechanisms that provide safe and efficient data transmission over unidirectional links.

Using unidirectional links for data communications is problematic. Although stable and usable unidirectional links can provide shorter paths to reach certain destinations, upstream nodes of unidirectional links may create severe interference at the downstream nodes unintentionally when the links are temporary or unnoticed. In addition, the coordination between the nodes at both ends of a unidirectional link requires sending information over a multihop path, which requires larger scale knowledge about the network topology than simple neighbor information. Proper use of unidirectional links demands a topology-dependent channel access scheme to ensure fast and impromptu data transmission, without incurring collisions.

Channel access control in ad hoc networks with unidirectional links can be either contention-based or scheduled. Contention-based methods are not well suited to wireless terrestrial networks with unidirectional links, because they all need feedback from the receiver, which requires medium access control (MAC) control packets to traverse multiple hops from receiver to sender. Even the ALOHA protocol applied on terrestrial links requires an acknowledgment to be sent to the sender of a packet in order for the sender to decide if there was a collision or not.

Scheduled access schemes prearrange or negotiate a set of time tables for individual nodes or links before hand, such that the transmissions from these nodes or on these links are collision-free in the time slots and frequency bands. Previous MAC protocols based on scheduling do not work in multihop packet radio networks with unidirectional links, because of their dependence on collision-avoidance handshakes among nodes, which work correctly only over bidirectional links [5] [16] [21] [24]. Only a few algorithms based on topology-transparent transmission scheduling are viable for handling unidirectional links in multihop networks [3] [4] [20]. However, in these protocols, the sender is unable to know which neighbor(s) can correctly receive its packet in a particular slot. This implies that the sender has to send its packet in the various slots in a frame and that the frame length (number of slots) must be larger than the number of nodes in a two-hop neighborhood and depends on the network size, which is less scalable.

The problem of deriving an optimal channel access schedule in multihop network is NP-hard [6] [7] [18]. Polynomial algorithms are known to achieve suboptimal solutions. A unified framework for (T/F/C)DMA channel assignment, called UxDMA, was described by Ramanathan [17] to compute a k-coloring of a directed graph in polynomial steps. The heuristic consists of starting coloring nodes or edges randomly or sequentially according to vertex degrees, and deriving a minimal number of colors such that a set of constraints on the nodes or links are satisfied. The constraints on the coloring pattern comprehend such commonly known interferences as direct and hidden-terminal interferences [22]. Unfortu-

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nately, the need for global topology collection and schedule dissemination poses a major challenge for applying this scheduling approach in mobile ad-hoc networks.

This paper presents a distributed MAC protocol for ad hoc networks with unidirectional links called PANAMA (Pairwise link Activation and Node Activation Multiple Access). PANAMA supports collision-free broadcasting and unicasting, without either repetitious schedule adjustments due to network topology changes or global topology information. The only information PANAMA needs to generate collision-free schedules at a node is the two-hop neighbor information of the node. Section 2 describes network concepts and topology notation used to describe ad hoc networks with unidirectional links. Section 3 describes our approach to modeling contention in networks with unidirectional links. Section 4 presents a new distributed contention resolution algorithm on which PANAMA is based. Section 5 describes PANAMA, which is based on an algorithm for collision-free unicast transmissions and an algorithm for collision-free broadcast transmissions. Section 6 describes the neighbor protocol needed to handle mobility. Section 7 addresses the performance of PANAMA by simulation. Section 8 concludes the paper.

2. TOPOLOGY ASSUMPTIONS

The topology of a network with unidirectional links can be abstracted as a directed graph $G = (V, A)$, where V is the set of nodes, and A is the set of directional links between nodes, i.e., $A \subseteq V \times V$. We assume that each node in the multihop packet radio network has a unique identifier, and is mounted with an omnidirectional radio transceiver. A link $(u, v) \in A$ means that node v is within the radio transmission range of node u and that a possible data transmission channel exists from node u to node v. A link $(u, v) \in A$ does not necessarily mean that $(v, u) \in A$ in unidirectional networks.

If a link $(u, v) \in A$, node u and v are called the *head* and *tail* of the link, respectively. Sometimes, node u is called *upstream neighbor* of node v, and node v is the *downstream neighbor* of node u. Similarly, link (u, v) is called *downstream link* of node u, and the *upstream link* of node v. We denote the set of upstream and downstream neighbors of a node i as U_i and D_i, respectively. Two distinct nodes adjacent to the same node are called *two-hop neighbor*s to each other.

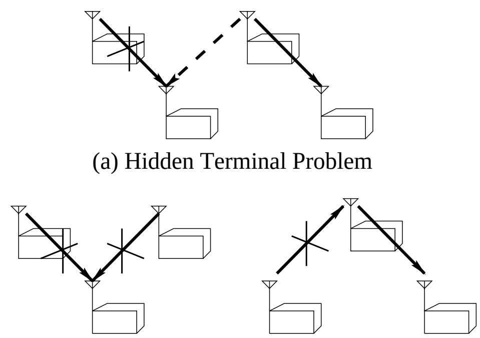
A unidirectional link is always first detected by the tail of the link, and its existence is propagated back to the head of the link. Hence, there is causal asymmetric knowledge about the existence of a unidirectional link at the head and tail of the link. For instance, if $(u, v) \in A$, then $v \in D_u$ implies $u \in U_v$, but not the opposite. The establishment of a downstream neighbor at a node requires a cycle including the link to exist in the network [2].

Each node or link of the network has a bandwidth property that indicates the portion of the channel available to the node or link. The bandwidth assigned to a node i is denoted by bw_i, which is a floating-point number that ranges over $[0, 1)$. Likewise, the bandwidth of a link (u, v) is a floating-point number $bw_{(u,v)} \in [0, 1)$. The bandwidth is requested by the node or the head of the link dynamically, depending on the needs from network-level protocols.

If node u is an upstream neighbor of v, and $bw_{(u,v)} = 0$, we say that the head is an *upstream-only* neighbor of the tail, which means the head does not send data packets to the tail, but may only interfere at the tail of the link.

3. MODELING CONTENTION

In multihop wireless networks, contending entities are nodes or links between nodes. A contention between two entities is a situation in which simultaneous activation of one entity would render the activation of another unsuccessful. Collisions happen in three cases, as illustrated in Figure 1 [19]. This indicates that nodes within two hops cannot transmit in the same time, code, or frequency division to ensure collision-freedom. To enforce this, a node needs to at least know its neighbors and its neighbors' neighbors for channel access scheduling.



(a) Hidden Terminal Problem

(b) Direct Interference (c) Self Interference

Figure 1: Examples of Collision Types

We make the following assumptions:

1. A radio module of each node may either transmit or receive data packet at a time, but not both.
2. Every entity already knows the set of its contenders by the neighbor protocol.
3. A time, code, or frequency division unit is a *contention context*, and each contention context is identifiable.

In the description of our collision resolution algorithm, we consider the time slot number as the identifier of a contention context. Code and frequency assignments are left out until individual MAC protocols are specified. In a time division multiple access scheme, each time slot can be numbered, because nodes must be synchronized at the granularity of a time slot.

The contention-resolution problem (CRP) can thus be stated as follows:

> **CRP:** *Given a set of contenders, M_i, against an entity i in contention context t, how does i decide if itself is the winner among the set $M_i \cup \{i\}$ without conflicts with others?*

4. CONTENTION RESOLUTION ALGORITHM

The channel assignment problem in the time, frequency and code domains has traditionally been treated as a graph coloring problem. A k-coloring on the nodes or links of the network topology graph corresponds to k sequential activations to the nodes or links in the same color without collisions at the intended receivers, thus obtaining temporal and spatial reuse of the available bandwidth. The schedules derived from graph coloring are static, because the network topology has to remain unchanged; otherwise, a new schedule is re-computed and broadcast after new topology information is collected. In mobile networks, this consumes a significant portion of the scarce wireless bandwidth. The efficiency of static coloring algorithms may also suffer from the fact that some of the colors could be so rarely used for coloring that the activation of nodes or links in those colors can not engage sufficient spatial reuse of the channel in multihop networks.

We adopt a different approach to graph coloring to solve the CRP problem. First, node or link activation scheduling is dynamic, such that a different schedule is established in each contention context (e.g., each time slot). Second, the coloring needs only two colors, r and b. An entity i gives itself color r if its has the highest priority amongst its contenders in a contention context. Otherwise, i colors itself with b. Nodes in color r are active in the corresponding contention context. Third, the color r is used in each contention situation to the maximal degree without any collision possibility. Fourth, the maximum topology information required in the coloring process consists of the one- and two-hop neighbor information of a node, instead of the complete topology of the network.

To describe our solution to the CRP problem, we assume that primary operants in mathematical formulas are of fixed length, and the sign '$\oplus$' lends to carrying out concatenation operation on its operants.

During the contention context t, the following algorithm solves the CRP problem:

CRA-FP (Floating Point):

1. Compute a priority for each member k in set $M_i \cup \{i\}$, which is denoted by p_k^t:
$$p_k^t = \sqrt[bw_k]{\mathtt{Rand}(k \oplus t)}, k \in M_i \cup \{i\} \quad (1)$$
2. i wins the contention at t if:
$$\forall j \in M_i, p_i^t > p_j^t \quad (2)$$
Otherwise, i yields to other contenders. □

where $\mathtt{Rand}(x)$ is a floating-point pseudo-random number generator that produces a uniformly distributed random number over $[0, 1)$ using the random-seed x. bw_k is the bandwidth requested by entity k. If $bw_k = 0$, $p_k^t = 0$.

The following lemmas demonstrate that CRA-FP provides collision-free channel access, without creating deadlocks and in a fair manner.

LEMMA 1. *Access to the common channel is collision-free at all times.*

Proof: Because it is assumed that contenders have mutual knowledge and t is synchronized, the order of contenders based on the priorities is consistent at every participant. When the entity i has the highest priority in the set $M_i \cup \{i\}$, each $k \in M_i$ yields to i, and allows i to access the common channel collision-free. □

LEMMA 2. *The contention resolution algorithm is live.*

Proof: In multihop wireless networks where we have a finite number of entities to consider, the algorithm always results in at least one or more winners in each contention situation, because CRA-FP gives a floating-point priority to each entity, and multiple locally maximal priorities may exist in the network. The case without a winner elected where two priorities are the same and also the global maximum is rare and negligible. Therefore, CRA-FP allows live utilization of the common channel in each contention context. □

LEMMA 3. *Each contending member has a fair share of the common channel, the portion of which available to an entity is relative to the encountered contentions by the entity. That is:*

$$q_i = \frac{bw_i}{\sum_{k \in M_i \cup \{i\}} bw_k}. \quad (3)$$

Proof: CRA-FP basically generates a random *permutation* of the contending members, the order of which is decided by the priorities of all participants. Since the priorities change from time to time, the permutation also varies randomly such that an entity i has certain probability to win in each contention context.

Without loss of accuracy, we assume that the priorities of different entities are always distinct. For convenience, we temporarily introduce random variable X_k and Y_k to denote the result of function $\sqrt[bw_k]{\mathtt{Rand}(k \oplus t)}$ and $\mathtt{Rand}(k \oplus t)$, respectively. This gives us the following relations:

$$X_k = p_k^t = \sqrt[bw_k]{Y_k}, k \in M_i \cup \{i\}.$$

In addition, $P\{Y_k < y\} = y$ since the random variable Y_k is uniformally distributed over the range $[0, 1)$. Thus the cumulative distribution function (CDF) of the derived random variable X_k is:

$$F_k(x) = P\{X_k < x\} = P\{\sqrt[bw_k]{Y_k} < x\}$$
$$= P\{Y_k < x^{bw_k}\} = x^{bw_k}$$

which gives the probability density function (PDF) of random variable X_k as:

$$f_k(x) = F_k'(x) = bw_k \cdot x^{bw_k - 1}$$

Specifically, when the priority of entity i is x, the probability that entity i wins the contention is derived from Eq. (2):

$$q_i(x) = P\{X_k < x, k \in M_i\} = \prod_{k \in M_i} P\{X_k < x\}$$
$$= \prod_{k \in M_i} x^{bw_k} = x^{\sum_{k \in M_i} bw_k}$$

Since the value of x ranges in $[0, 1)$, we achieve the probability of entity i winning the contention by the following integration:

$$q_i = \int_0^1 q_i(x) \cdot f_i(x)dx = \int_0^1 x^{\sum_{k \in M_i} bw_k} \cdot bw_i \cdot x^{bw_i - 1}dx$$
$$= \frac{bw_i}{\sum_{k \in M_i \cup \{i\}} bw_k}$$

□

5. PANAMA

PANAMA is a distributed multiple access control protocol that combines two channel access scheduling algorithms based on time-slotted code-division multiple access scheme using direct sequence spread spectrum (DSSS) transmission techniques. The first scheduling algorithm used in PANAMA is NAMA-UN (Node Activation Multiple Access for Unidirectional Networks), which is a node-activation oriented channel access algorithm suitable for broadcasting in wireless networks with unidirectional links. The second scheduling algorithm in PANAMA is PAMA-UN (Pair-wise link Activation Multiple Access for Unidirectional Networks), which is a link-activation oriented channel access control algorithm suitable for unicasting in wireless networks with unidirectional links.

In both NAMA-UN and PAMA-UN, a node is in the *receiving mode* when it does not win the contention. It listens to the traffic in the channel by tuning its reception code to the potential transmitter. In NAMA-UN, the potential transmitter is an upstream neighbor that has the highest node-priority among the upstream neighbor set. In PAMA-UN, the potential transmitter is the head of an upstream link with the highest link-priority among the upstream link set.

PANAMA combines NAMA-UN and PAMA-UN to support unicast and broadcast traffic efficiently. Deciding on what portion of the channel to assign to each protocol is a very pragmatic decision that depends on expected traffic patterns in the network. In this paper a fixed channel allocation is assumed for NAMA-UN and PAMA-UN, with each section dedicated to NAMA-UN and PAMA-UN lasting for T_{nama} and T_{pama} time slots, respectively. Accordingly, broadcast traffic always waits for the NAMA-UN section, while unicast traffic is sent during the PAMA-UN section, or NAMA-UN section if broadcast traffic is not present.

We do not address synchronization issues for time division channel access, but suggest achieving it by either: (a) listening to data traffic in the network, and aligning time slots to the latest starting point of a complete packet transmission by one-hop neighbors; or (b) such other means as using GPS (global positioning systems) timing signals and the network time protocol (NTP).

Code assignment in a network based on DSSS can be based on transmitter-oriented (also known as TOCA), receiver-oriented (ROCA) or a per-link-oriented code assignment (POCA) schemes [9] [13]. Because a node can only transmit or receive at one time on a single code, it is unnecessary to assign different codes to links incident to a single node as in a POCA scheme. Furthermore, as Figure 2 illustrates, simply using two-hop topology information at each node is insufficient to resolve collisions in a network with unidirectional links using a ROCA scheme. In Figure 2, the number beside each node gives the current receive-code assigned to the node. A unidirectional link (b, c) partitions the network. Node b is unaware of node c. Since a is beyond two-hop topology information perceived by e, node e is never certain about the collision threat from b when it sends data to c. Accordingly, the algorithms used in PANAMA are based on a TOCA scheme.

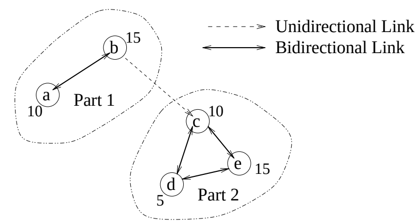


Figure 2: Irresolvable Situation in ROCA

We assume that a pool of quasi-orthogonal pseudo-noise codes, $C_{pn} = \{c^k\}$, are available for each node to choose from, and the pseudo-noise codes inside C_{pn} are sorted as $c^0 < c^1 < \ldots < c^{|C_{pn}|-1}$. The code for each node is computed in each time slot so that the contention situation is different from time slot to time slot. A pseudo-noise code c_i from C_{pn} is assigned to a node i in time slot t according to the following algorithm:

$$c_i = c^k, k = \texttt{iRand}(i \oplus t) \ \texttt{mod} \ |C_{pn}|. \tag{4}$$

where $\texttt{iRand}(x)$ is an integer pseudo-random number generator that produces a random integer using input x as the randomizing seed.

To describe the algorithms used in PANAMA, we assume that each node has already acquired the knowledge about its one- and two-hop neighbors and their bandwidth allocations. The goal of node activations and link activations at a node i is to send data packets to a subset of downstream neighbors, which is defined as:

$$R_i = \{k \mid k \in D_i, bw_{(i,k)} > 0\} \tag{5}$$

R_i is called the *receiver set* of node i that has a positive link bandwidth flowing out of i. Downstream links of node i that are assigned 0 bandwidth are either unknown to i because of unidirectional drawbacks or unusable because of topology control mechanisms.

Because we have a limited number of pseudo-noise codes for assignment, it is possible that multiple nodes share the same code. The methods of resolving transmissions on the same code are described below.

5.1 NAMA-UN

In NAMA-UN, every node is associated with some amount of bandwidth. NAMA-UN decides whether a node i can transmit in a time slot t, such that its receiver set receives the data packet without collisions. Therefore, the contenders for node i are of the following three kinds:

1. The receiver set of node i, R_i;
2. All of i's upstream neighbors, U_i;
3. All upstream neighbors of nodes in i's receiver set, i.e., $\bigcup_{k \in R_i} U_k$

Accordingly, the set of contenders for node i is:

$$M_i = U_i \cup R_i \cup \left(\bigcup_{k \in R_i} U_k \right) \tag{6}$$

which contains all nodes that may sent information to or receive information from i and those that may incur interference at i's receiver when i transmits.

NAMA-UN decides the activation of node i at time slot t according to following algorithm:

NAMA-UN:

1. Compute the priority p_k^t of every node $k \in M_i \cup \{i\}$ using Eq. (1).
2. Exit if Eq. (2) does not hold.
3. Exit if any upstream-only neighbor of i's downstream neighbors possesses the same transmission code as i's, i.e.,
$$\begin{aligned} \exists v \in R_i \text{ and } u \in U_v \text{ and } \\ bw_{(u,v)} = 0 \text{ and } c_i = c_u \end{aligned} \tag{7}$$
where c_i and c_u are obtained from Eq. (4).
4. Broadcast in current time slot t. $\square$

Step 3 avoids possible hidden terminal conflicts from v's upstream neighbor u when node u is assigned the same code as i's and does not know about link (u, v) due to the asymmetric properties of unidirectional links.

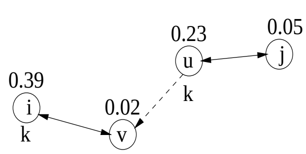


Figure 3: Collision Resolution in NAMA-UN

Figure 3 illustrates an example of collision avoidance in NAMA-UN. The numbers beside each node are the current priorities of the nodes, and k is the code assigned to u and i. Though both i and u can transmit on code k by the first two steps in NAMA-UN, but i will be deactivated in the third step which avoid collision at node v.

5.2 PAMA-UN

Unlike NAMA-UN, a link in PAMA-UN may be assigned 0 bandwidth depending on following two situations:

1. When a link is initially detected by its tail, the bandwidth of the link is set to 0 by the tail.
2. If a link is able to propagate back to the head, the bandwidth of the link can be set to any value in the rage $[0, 1)$. A node may choose to set the bandwidth request of the link to 0 because of data flow controls.

With synchronized information about local topologies and bandwidth allocations, PAMA-UN decides whether a directed link (u, v) with *positive* bandwidth can be activated by node u in time slot t. Herein, the set of contenders to link (u, v) are the incident links of u and v with positive bandwidths, excluding (u, v) itself. That is:

$$\begin{aligned} M_{(u,v)} = \{(x,y) \mid (x,y) \in E \textit{ and } bw_{(x,y)} > 0 \textit{ and } \\ (x \in \{u,v\} \text{ or } y \in \{u,v\}) \} - \{(u,v)\}. \end{aligned}$$

PAMA-UN:

1. Compute the priority $p_{(x,y)}^t$ of every link (x, y) in set $M_{(u,v)} \cup \{(u, v)\}$ using the following equation:
$$p_{(x,y)}^t = \sqrt[bw_{(x,y)}]{\texttt{Rand}(x \oplus y \oplus t)} \tag{8}$$
2. Exit if the following equation does not hold:
$$\forall (x,y) \in M_{(u,v)}, p_{(u,v)}^t > p_{(x,y)}^t \tag{9}$$
3. Compute the priorities of upstream neighbors of nodes in u's receiver set:
$$p_k^t = \texttt{iRand}(k \oplus t), k \in U_j, \forall j \in R_u. \tag{10}$$
where function $\texttt{iRand}(x)$ is given in Eq. (4).
4. Exit if either of the following two conditions holds:
   - One of the upstream-only neighbor of a u's receiver possesses the same transmission code as u. That is:
   $$\begin{aligned} \exists k \in U_j, \text{ where } j \in R_u \text{ and } \\ bw_{(k,j)} = 0 \text{ and } c_u = c_k \end{aligned} \tag{11}$$
   Code assignments, c_u and c_k, are obtained from Eq. (4).
   - One of the upstream links of a u's receiver is assigned positive bandwidth, and the head of the link possesses the same transmission code as u, and the priority of the head is greater than that of u. That is:
   $$\begin{aligned} \exists k \in U_j, \text{ where } j \in R_u \text{ and } bw_{(k,j)} > 0 \\ \text{and } c_u = c_k \text{ and } p_u^t < p_k^t. \end{aligned} \tag{12}$$
5. Activate link (u, v). $\square$

PAMA-UN encounters similar hidden-terminal problems as NAMA-UN. Using the sample network in Figure 3 as an example with the same transmission code assignments, collision happens at node v if link (i, v) and (u, j) are activated simultaneously on code k. PAMA-UN deactivates link (i, v) for the current time slot as described by step 4.

6. NEIGHBOR PROTOCOL

In both NAMA-UN and PAMA-UN, topology information within two hops of a node, including bandwidth allocation to nodes and links, plays a critical role. Unfortunately, in mobile networks, network topologies change frequently, which affects the transmission schedules of the mobile nodes. In PANAMA, the ability to detect and notify such changes relies on the neighbor protocol described in this section.

6.1 Signal Sections

Both NAMA-UN and PAMA-UN adopt dynamic code assignment for channel access. Therefore, it is impossible for a node to follow a new one-hop neighbor that transmits a data packet in various time slots on various codes. We have to use an additional time section, called the *signal section* that lasts for T_{signal} time slots after every L alternations of NAMA-UN and PAMA-UN for mobility management purposes. Nodes exclusively depend on the signals to detect new upstream neighbor.

Channel access in PANAMA is based on code division scheme but solely dependent on the current time slot number t as given in Eq. (13), similar to Eq. (4).

$$c_t = c^k, k = \texttt{iRand}(t) \bmod |C_{pn}|. \tag{13}$$

In addition, a time slot within the signal section is further divided into S_s time segments, which implies $T_{signal}S_s$ time segments in the signal section. Each time segment lasts long enough to send out a signal, illustrated in Figure 4.

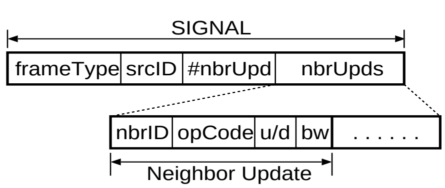


Figure 4: Signal Frame Format

In Figure 4, the field `nbrUpds` contains `#nbrUpds` neighbor updates, each including the updated neighbor ID (`nbrID`), the type of the neighbor (upstream/downstream as indicated in the field `u/d`) and corresponding bandwidth (`bw`) assigned to that neighbor. The value in the field `opCode` instructs the operation code, which may suggest *addition* or *deletion* of the neighbor from the transmitter's one-hop neighborhood. The field `u/d` takes one of four values using two bits as given in the following table:

`u/d`	Meaning
00	Update about the neighbor.
01	Update of the downstream link to the neighbor.
10	Update of the upstream link from the neighbor.
11	Update of the link with the neighbor in both directions.

where the value 00 indicates neighbor updates for NAMA-UN and all others are for PAMA-UN.

Using signals, a node may send topology changes or bandwidth adjustments. When a new mobile node is brought up, sending out signal is the first activity to notify its one-hop neighbors of its existence.

The number of time segments in the signal section, $T_{signal}S_s$, and the interval between signal sections, L in terms of NAMA-UN and PAMA-UN sections, depend on the average number of one-hop neighbors for each node and the frequency of topology changes. In general, the value of L is set small and the value of $T_{signal}S_s$ is set large for highly mobile networks so as to quickly adjust to topology variations.

Besides signals, one-hop neighbor updates are also propagated using broadcast data packets in the NAMA-UN section so that the update information of a node gets to all its neighbors efficiently. One-hop neighbor updates are piggyback in the option field of a data frame whenever necessary. Figure 5 illustrates the data packet format, which includes similar neighbor update fields as in Figure 4.

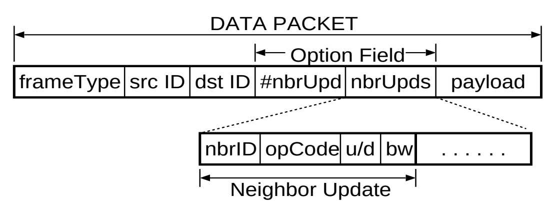


Figure 5: Data Frame Format

6.2 Neighbor State Maintenance

In a mobile network, topology changes happen in the following scenarios as far as the operations of NAMA-UN and PAMA-UN is concerned:

- The establishment of a new link, such as new upstream link detected by a node;
- The disappearance of an existing link, such as one-hop neighbors departing from each other;
- Link state changes, such as bandwidth reassignment to a node or a link.

To ascertain the liveliness of outgoing links, it is required that a node sends out a signal packet after every certain period of time. The time period is derived such that it is highly probable that every two-hop neighbor of a node can transmit at least one signal packet during the period. Therefore, the signal transmitted by the node is least likely to collide with

others. We consider two-hop instead of one-hop neighbors because the contenders of a node for broadcasting signals in the channel are two-hop neighbors of the node.

The length of the period during which every two-hop neighbor of a node may transmit can be formulated as an occupancy problem in combinatorial mathematics [8] [11], which pursues the probability of having m empty cells after randomly placing r balls into n cells, where r corresponds to length of the period, and n corresponds to the number of two-hop neighbors of the node. We directly use the result on the probability of leaving exactly m cells empty, which is:

$$p_m(r,n) = n^{-r} \binom{\text{n}}{\text{m}} \sum_{v=0}^{n-m} (-1)^v \binom{\text{n-m}}{\text{v}} (n-m-v)^r \quad (14)$$

We choose a r value for the network such that the probability of every two-hop neighbor having transmitted at least one signal is greater than 0.99, i.e. $p_0(r,n) > 0.99$. Figure 6 demonstrates the interval values in terms of time segments for successive signal transmissions versus different numbers of two-hop neighbors.

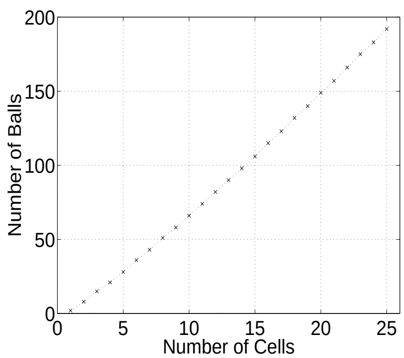


Figure 6: Signal Intervals vs. Number of Two-hop Neighbors Such That $p_0(r,n) > 0.99$

When r time segments pass by at a node, the node chooses a random time segment of the next signal section to send a signal so that signal transmissions are evenly distributed and encounter very few collisions.

When the connection between two nodes is unidirectional, we have to rely on more complex control protocols in the upper layer to coordinate the neighbor information between adjacent nodes because it requires multihop propagations of the link states. A neighbor protocol was proposed in [2] for this purpose. PANAMA provides a set of control interfaces (APIs) for (a) reporting new upstream links or incident link state changes, and (b) receiving control messages from other control protocols for neighbor maintenance, such as addition of a new neighbor, deletion of an existing neighbor, and propagating these control messages using either NAMA-UN broadcast packets or signals.

Figure 7 depicts the operations for establishing a new bidirectional connection using signals only between two nodes, a and b. The links marked beside each node show the formation of the knowledge about the connection between a and b at each node. The events are described as follow:

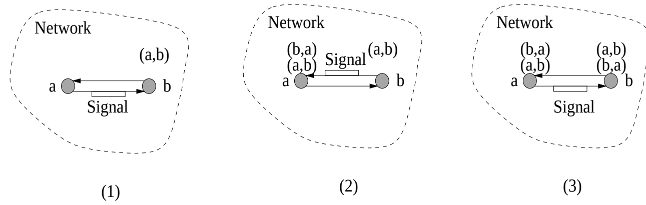


Figure 7: Link State Propagation

1. Node a waits for a certain period to transmit a signal;

   If b receives the signal from a for the first time, it triggers b to send a second signal after a random number of time segments to notify its one-hop neighbors of the new upstream link (a,b).

2. If a receives the second signal, a acknowledges b as a new upstream neighbor, and notifies link (b,a) as well as (a,b) to its upper layer control protocols, which in turn assign bandwidth property to link (a,b). New link information about (a,b) and (b,a) is propagated back to b.

3. If b receives the third signal, b also knows its downstream link (b,a). Link (b,a) is reported to b's upper layer control protocols for bandwidth assignment, and propagated back to a.

If the companion link (b,a) does not exist for link (a,b) in Figure 7, a needs more complex steps by the upper layer control protocols for propagation of link (a,b) and other coordinations between a and b.

7. PERFORMANCE

The delay and throughput attributes of PANAMA are studied by simulations in static network topologies with unidirectional link. Many configurable parameters in the protocol are simplified, such as the durations of different sections.

The simulations are guided by the following parameters and behaviors, and most numbers are more of empirical preferences rather than theoretical conjectures:

- The networks are generated by randomly placing 100 nodes within an area of 1000×1000 square meters. To simulate infinite plane that has constant node placement density, the opposite sides of the square are seamed together, which visually turns the square area into a torus.
- Signal propagation in the channel follows the free-space model and the effective range of radio is determined by the power level of the radio. The power range of a radio is randomly chosen from the range $[150m, 300m]$, which creates unidirectional links.
- To simulate deactivated or unusable unidirectional links in the network, we assume that 10% of the network links are assigned 0 bandwidth, while all other links and all nodes are assigned bandwidth 1.0.

- Bandwidth of the radio channel is 2 Mbps.
- A time unit in the simulation equals one time slot. A time slot last 8 milliseconds, including guard time, long enough to transmit a 2KB packet.
- $L = 1$, $T_{nama} = 25$, $T_{pama} = 95$, $T_{signal} = 5$, thus the period for one alternation of NAMA-UN, PAMA-UN and signal section is 1 second.
- In NAMA-UN and PAMA-UN, 30 pseudo-noise codes are available for code assignments, i.e., $|C_{pn}| = 30$.
- All nodes have the same packet arrival rate λ, pct_b percent of which is broadcast traffic and the rest is unicast traffic. The destinations of the unicast packets in PAMA-UN are distributed on all outgoing links with positive bandwidth, proportional to the probability of activating the link.
- Packets are served in First-In First-Out (FIFO) order.
- The duration of the simulation is 800 seconds (equal to 100000 time slots), long enough to compute the metrics of interests.

Four main factors influence the system delay and throughput attributes of PANAMA, namely: the data traffic load on each node (denoted by λ), the portion of broadcast traffic in the overall traffic (pct_b), the portion of inactive directional links that only interfere with other transmissions (pct_u) and the radio transmission ranges that affect the contention levels at each node (r). To manifest the effects of these different parameters on the system delay and throughput, we fix three of the four factors and variate the remaining parameter to simulate the operations of PANAMA. The fixed values of each simulation put lenient stress on the network delays and throughput. Thus, we obtain four scenarios:

Scenario	Values of Fixed Parameters	Variable
1	pct_b=0.05, pct_u=0.1, r=100	λ
2	λ=0.06, pct_u=0.1, r=100	pct_b
3	λ=0.06, pct_b=0.05, pct_u=0.1	r
4	λ=0.06, pct_b=0.05, r=100	pct_u

Table 1: Four Scenarios and Their Parameters

Secondly, we also simulate the static scheduling algorithm, UxDMA, specified in [17], for comparison with PANAMA in the same simulation scenarios with as many similar parameters as possible, such as percentage of inactive links and channel divisions into NAMA-UN, PAMA-UN and signal sections, where UxDMA uses a different coloring scheme for each section. The criteria for coloring nodes in the broadcast section and links in the unicast section are given by the following table:

Section	Colored Object	Constraint Set
Broadcast	Node	$\{V_{tr}^0, V_{tt}^1\}$
Unicast	Link	$\{E_{rr}^0, E_{tt}^0, E_{tr}^0, E_{tr}^1\}$

The meaning of each symbol is referred to the original paper in [17].

The constraint E_{tr}^1 in UxDMA eliminates hidden terminal problem as illustrated in Figure 1(a). Furthermore, to make a fair comparison between UxDMA and PANAMA, nodes in UxDMA are assigned transmission codes so that constraint E_{tr}^1 is allowed when transmitters have different transmission codes.

Because the coloring on nodes and links is closely coupled with code assignments, the code assignments are carried out only once at the beginning of each simulation, and remain static throughout the simulation as well as the color assignments. Nodes are assigned codes randomly chosen from the code base C_{pn}.

In addition, inactive links in the network topology are not colored but taken into account when coloring links and nodes, so that these links incur interference at other nodes.

The number of colors used by UxDMA determines the time frame during which every entity is able to access the channel once. A time frame, unfinished in either NAMA-UN or PAMA-UN section, continues in the upcoming section of the same type.

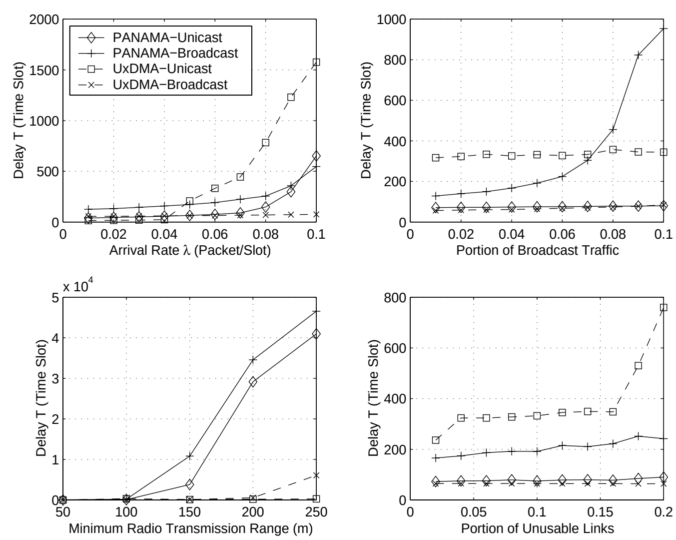


Figure 8: Average Packet Delays In Multihop Networks

Figure 8 and 9 show the delay and throughput attributes of PANAMA and UxDMA in multihop networks of the four scenarios.

In all scenarios except scenario 3, unicast traffic has lower delays in PANAMA than in UxDMA; however, PANAMA performs worse than UxDMA for broadcast traffic. Likewise, the network throughput is almost the same in both PANAMA and UxDMA when the network load remains at sustainable levels. In scenario 3, however, both unicast and broadcast traffics endure much longer delay and worse network throughput when the transmission ranges increase in PANAMA, because of higher contention levels from longer radio transmission ranges that increase the probability of code assignment conflicts between two-hop neighbors, and lead to many aborted transmission due to collision avoid-

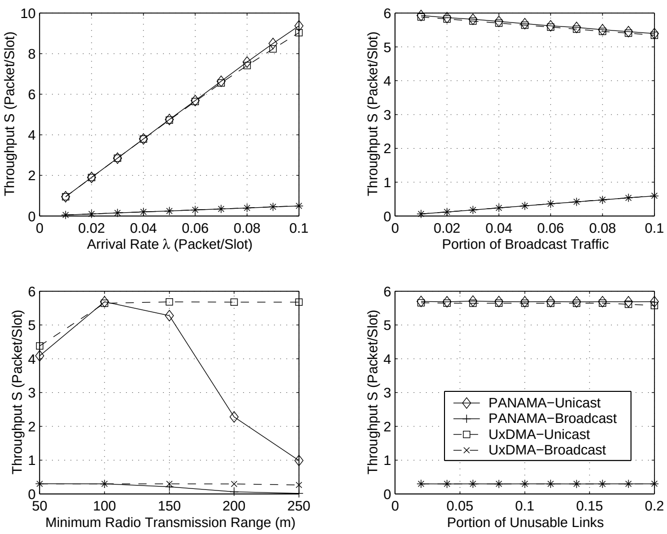


Figure 9: Packet Throughput Of Multihop Networks

ance.

Overall, NAMA-UN performs worse than its counterpart of static scheduling, while PAMA-UN is better than the static link scheduling algorithm in UxDMA. However, PAMA-UN cannot endure high contention levels in multihop networks due to conflicts in code assignment. With power control and topology control algorithms that modulate the number of one-hop neighbors of each node, PAMA-UN gives the best mechanisms for data transmission in mobile environments.

Furthermore, PANAMA allows dynamic channel allocation to nodes and links by floating point granularity, which is not possible in static scheduling scheme where the bandwidth has to be integer numbers, equal to the number of colors assigned to that entity. However, PANAMA does have disadvantages in that the intervals between successive transmissions by a single entity is governed by a geometric distribution.

8. CONCLUSION

We have introduced a new approach to contention resolution in networks with unidirectional links that uses local topology information to dynamically determine the activation of a node or a link in each contention context. The algorithm used as the basis of our approach eliminates much of the complexity of prior collision-free scheduling approaches and improves channel utilization. Based on this basic approach, PANAMA was specified, which incorporates both node-activation and link-activation channel access scheduling in packet radio networks. It was shown that PANAMA is suitable for topology control and resource management in mobile ad hoc networks that contain unidirectional links.

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